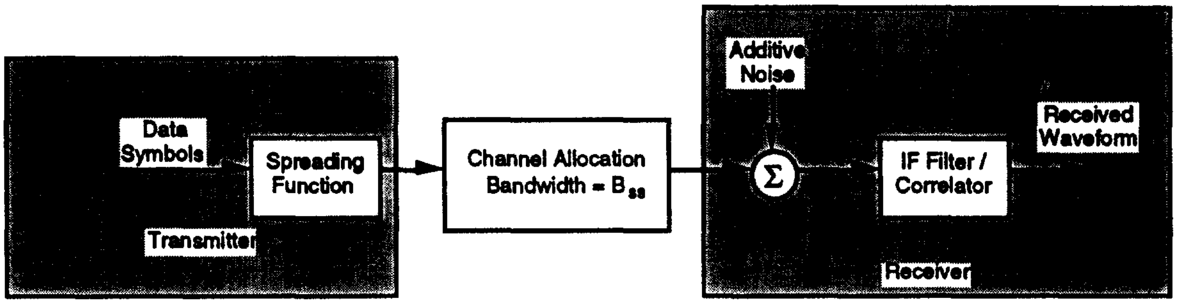


Figure 1: Simplified Model of a Spread Spectrum System

The received waveform is processed through an IF and compressive delay line which serves to bandlimit the noise and form a correlation peak indicative of the transmitted information symbol. Figure 2 represents a typical correlation peak out of the correlator; this diagram will serve to derive the desired relationship.

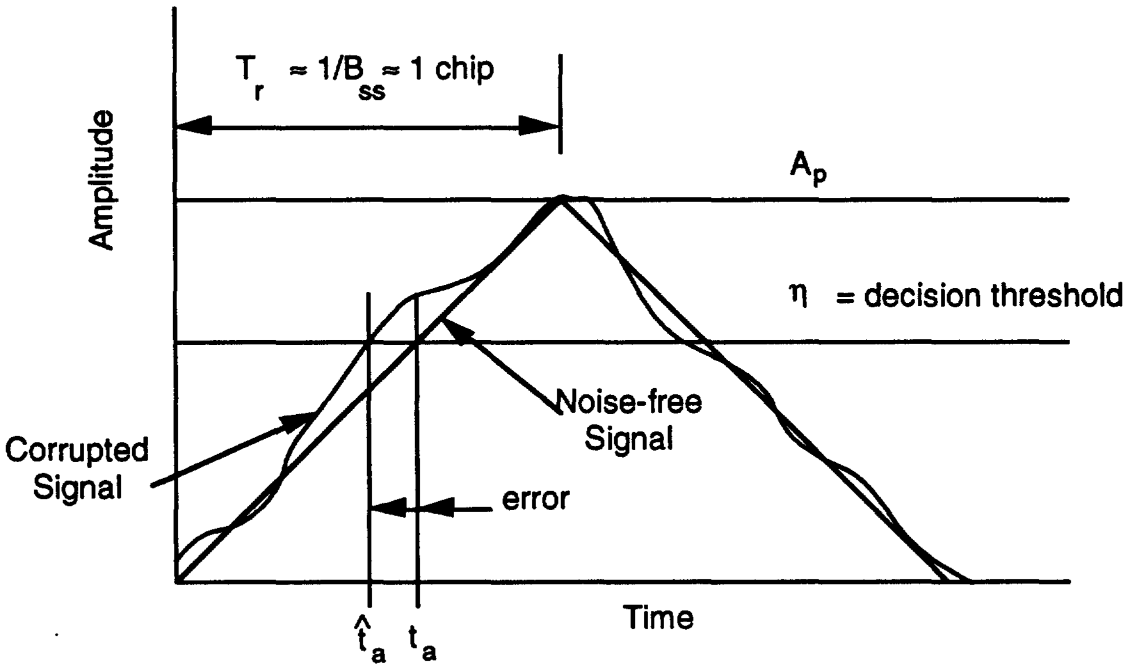


Figure 2. Signal Out of Correlator/IF

At $\hat{t}_a$, the time at which the correlator output waveform crosses the decision threshold, the signal can be decomposed into the sum of the noise-free signal term and a noise term described as

$$A(\hat{t}_a) + n(\hat{t}_a) = \eta \tag{1}$$

Assuming that the rising edge of the correlator output pulse is approximately linear, the amplitude of the noise-free signal at the estimated time of arrival can be written as

$$A(\hat{t}_a) = \frac{\hat{t}_a}{T_r} A_p \tag{2}$$

Substituting equation (2) into equation (1), and rearranging terms, the estimated time of arrival is found to be

$$\hat{t}_a = \left[\eta - n(\hat{t}_a)\right] \frac{T_r}{A_p} \tag{3}$$

Within an arbitrary scale factor (which we take to be unity), the peak signal voltage at the correlator output is proportional to the square root of the signal power at the correlator output. That is,

$$A_p = \sqrt{S_{out}} \tag{4}$$

Substituting this into equation (3),

$$\hat{t}_a = \left[\frac{\eta - n(\hat{t}_a)}{\sqrt{S_{out}}}\right] T_r \tag{5}$$

We are interested in the amount of timing jitter on the time of arrival (TOA) estimate, and therefore compute the variance of the random variable $\hat{t}_a$ which is given by

$$VAR(\hat{t}_a) = \sigma_{\hat{t}_a}^2 = E\left[(\hat{t}_a)^2\right] - \left[E(\hat{t}_a)\right]^2 \tag{6}$$

Taking the expected value of $\hat{t}_a$ as defined in (5), and assuming that the noise is zero mean, we get that the mean of the TOA estimate is:

$$E(\hat{t}_a) = T_r \left[\frac{\eta}{\sqrt{S_{out}}} - \frac{E(n(\hat{t}_a))}{\sqrt{S_{out}}}\right] = \frac{\eta T_r}{\sqrt{S_{out}}} = t_a \tag{7}$$

This is a comforting result, saying that the mean of the random variable $\hat{t}_a$ is the actual "noise-free" arrival time t_a. Therefore, the estimate is unbiased.

The variance of $\hat{t}_a$ (in sec^2) is determined as

$$
\begin{aligned}
\sigma^2_{\hat{t}_a} &= \left\{\left[\left(\frac{\eta - n(\hat{t}_a)}{\sqrt{S_{out}}}\right)T_R\right]^2\right\} - \left[E(\hat{t}_a)\right]^2 \\
&= \frac{\eta^2 T_r^{\ 2}}{S_{out}} - \frac{2\eta E(n(\hat{t}_a))T_r^{\ 2}}{\sqrt{S_{out}}} + \frac{E\left[n^2(\hat{t}_a)\right]T_r^{\ 2}}{S_{out}} - \frac{\eta^2 T_r^{\ 2}}{2S} \\
&= \frac{E\left[n^2(\hat{t}_a)\right]T_r^{\ 2}}{S_{out}}
\end{aligned}
\tag{8}
$$

For zero mean noise, the noise power at the correlator output is simply the variance of the random process $n(t)$, given by

$$N_{out} = E[n^2(\hat{t}_a)] \tag{9}$$

Since the correlator output pulse rise time (one chip period) is approximately equivalent to the inverse of the spread spectrum bandwidth, (8) and (9) can then be combined to yield

$$\sigma^2_{\hat{t}_a} = \frac{1}{B_{ss}^{\ 2}\left(S/N\right)_{out}} \tag{10}$$

In order to reduce the variance of the TOA error, M estimates are averaged

$$M = \left(\frac{\sigma_{\hat{t}_e}}{\sigma_{\hat{t}_\Sigma}} \right)^2 \tag{13}$$

Let R represent the required RMS timing error, $\sigma_{\hat{t}_e}$, and substitute equation (10) into equation (13)

$$M = \left(\frac{1}{RB_{ss}\sqrt{\left(S/N\right)_{out}}} \right)^2 = \frac{1}{R^2 B_{ss}{}^2 \left(S/N\right)_{out}} \tag{14}$$

The parameter which we wish to quantify is the rate at which position fixes can be made. This can be approximated as the reciprocal of the measurement period. This gives

$$F_{msr} = \frac{1}{T_{msr}} = \frac{1}{MT_s} \tag{15}$$

where T_s is the duration of a single spread spectrum sequence. Substituting equation (14) into equation (15):

$$F_{msr} = \frac{R^2 B_{ss}{}^2 \left(S/N\right)_{out}}{T_s} \tag{16}$$

The correlator input and output signal to noise ratios are related by the processing gain as

$$\left(S/N\right)_{out} = PG\left(S/N\right)_{in} \tag{17}$$

where the processing gain is the number of chips per symbol which can be written as

$$PG = B_{ss} T_s \tag{18}$$

Substituting (17) and (18) into (16):

$$F_{msr} = R^2 B_{ss}^3 \left(S/N\right)_{in} \tag{19}$$

This is the desired relationship for a narrow band noise limited case, which shows that for a given desired timing error standard deviation and fixed signal to noise ratio at the receiver input, the maximum rate at which position fixes can occur is proportional to the cube of the available bandwidth. This case could apply in a the case of a signal limited by a narrow-band, noise-like jammer.

For white noise of power spectral density $N_0/2$ Watts / Hz, the noise power at the correlator input is given by

$$N_{in} = \frac{N_0 B_{ss}}{2} \tag{20}$$

Substituting this result into (19) yields

$$F_{msr} = R^2 B_{ss}^2 \left(S_{in} / N_0 \right) \tag{21}$$

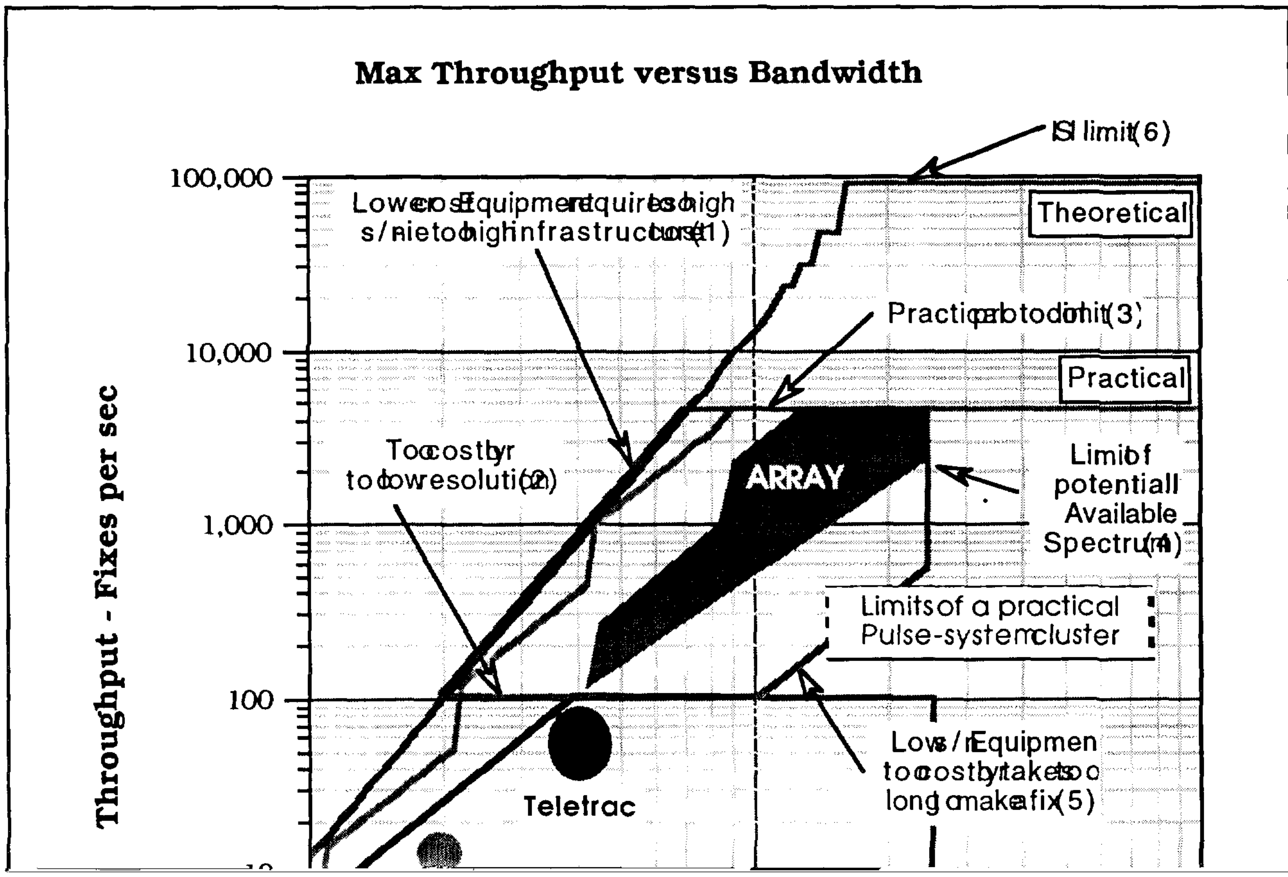
This is the desired relationship for a white noise limited case, which shows that for a given desired timing error standard deviation and fixed signal power, the maximum rate at which position fixes can occur is proportional to the square of the available bandwidth.

Interpretation

Equations (19) and (21) describe two very different practical conditions. Equation (21) describes the conditions which would pertain to a thermal noise limited case, such as might apply in clear spectrum with well designed equipment. However, we are dealing with the case of a shared spectrum, where typically the band is shared between relatively narrow band jammers.

Practical Bounds on the BW:Rate relationship

As discussed before, there a real, practical limits over which these rate relationships can be applied. We will use the graph in Figure 3 to explore them.



developed above. Multilaterating systems such as ARRAY are bound by somewhat arbitrary but practical limits illustrated by the pentagon having sides (1) through (5).

The theoretical curve shows the possible throughput for a particular time resolution and signal-to-noise ratio. It is limited at wider bandwidths by inter symbol interference (ISI) that would result from the pulse-expansion sequence duration being longer than the separation between pulses. The derivation of the line presumes an unconstrained size to the length of suitable expansion & compression sequences. However, the practical curve (stepped ramp) shows the results obtained by constraining the sequences to real values, (typically of length 2^n-1, where n has integer values). Practical rates are further limited at larger bandwidths to a maximum of about 5000 fixes per second by the requirements of typical radio-communication protocols, involved in the control and management of the radio-location process (addressing, operation codes, status, check characters, etc.) This requirement forms side (3) of the bounding area.

As the s/n ratio is increased, or the required resolution is reduced, the throughput increases. However, increasing the s/n ratio increases the cost of the infrastructure by requiring more base stations per square mile or more power output per base station, and the timing resolution can only be reduced to meet the operational requirements of the overall system. This creates the bound (1).

Boundary (2) is mainly economic one. At some ratio of infrastructure cost to system performance (in terms of throughput and resolution), and hence revenue generating capability, to infrastructure cost becomes too low for the system to be viable.

Boundary (4) is imposed by the potentially available bandwidth, which is a regulatory limit (or may be a financial limit if spectrum is auctioned).

Boundary (5) arises from equipment operating at too low a s/n ratio, requiring too great a complexity to dig the information out of the noise, or the system would be operating very slowly, severely restricting the throughput of the system.

Recommendations

For a fixed s/n or s/j ratio at the receiver input, the fixing rate varies with the cube of the available bandwidth in narrow-pulse correlating ranging system. Therefore, maximizing the efficiency of communication space (time and bandwidth) use is best served by the use of the largest possible bandwidth while within the practical bounds. However, while increasing the bandwidth beyond those bounds does not provide increased throughput, other benefits, such as increased resistance to interference and higher positioning resolution can be achieved.

Maximizing the use of bandwidth for position fixing provides disproportionate benefits in throughput terms. Therefore, for a given bandwidth being shared by multiple radio-location users, the throughput of the band is best served by allowing each user access to the whole of the band for a portion of the time, rather than by allowing each user continuous use of only a portion of the band.

Significant improvements in time efficiency can be realized by using a priori signal correlating techniques versus the more time consuming methods of phase determination that use only signal averaging. There is the added benefit to the use of correlation techniques. More robust treatment of the time of arrival distorting effects of multipath echoes is available since correlation of the a priori signal signature allows the echoes to be separated, and hence to be treated separately, either for identification of earliest time-of-arrival, or for summation to increase the energy-per-bit in data recovery.

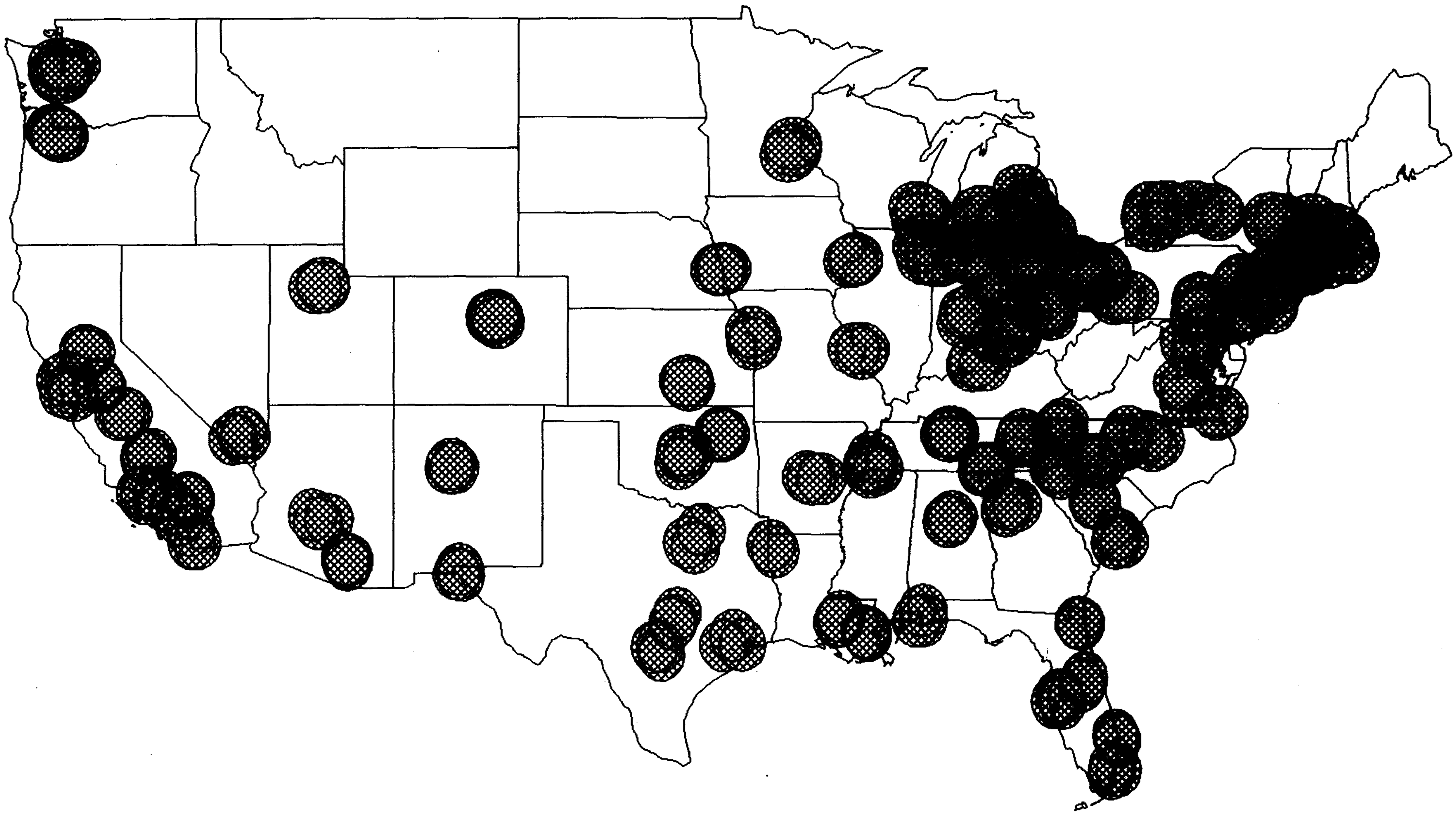
TAB

Exhibit B

Pactel and MobileVision Co-Channel Coverage.

These two maps show circles of 55 miles radius centered at the latitude and longitude coordinates of each FCC-licensed transmitter base station in the 902 to 928 MHz of Pactel Teletrac and METS/MobileVision. The coordinates have been taken from the FCC Master Frequency Table database. The MobileVision map shows 324 circles and the PacTel Teletrac map shows 1067 circles.

Both maps are on the same scale and projection. The projection is equidistant cylindrical with standard parallel 39° N and central meridian 96° W (eastern Kansas). The scale is approximately 312 miles per inch along the standard parallel. The circles above and below the standard parallel appear as ovals due to the projection.



METSDATA.TXT

METS/MobileVision Licensed Sites:
55-mile radius coverage areas

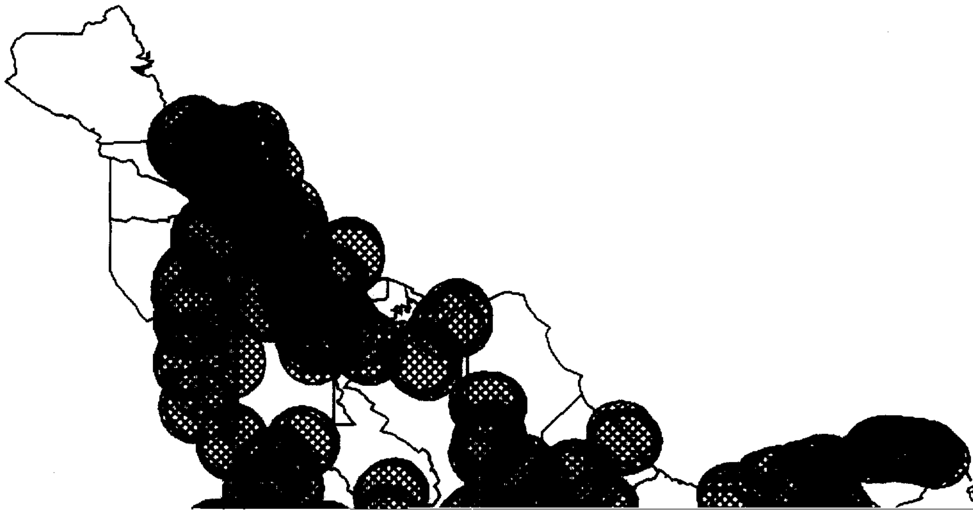


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Exhibit C

"Black-out" Zones Near Tag Stations

This set of three figures shows the effect that distance between a wide-area base station and a local-area tag reader would have on the size and extent of the signal "black-out" region that the wide-area system's mobile would experience near the local-area reader station. The contours show regions of constant link margin, with the dark zone indicating the extent of that zone within which the wide-area mobile's link-margin is below its 50% reliability receive threshold.

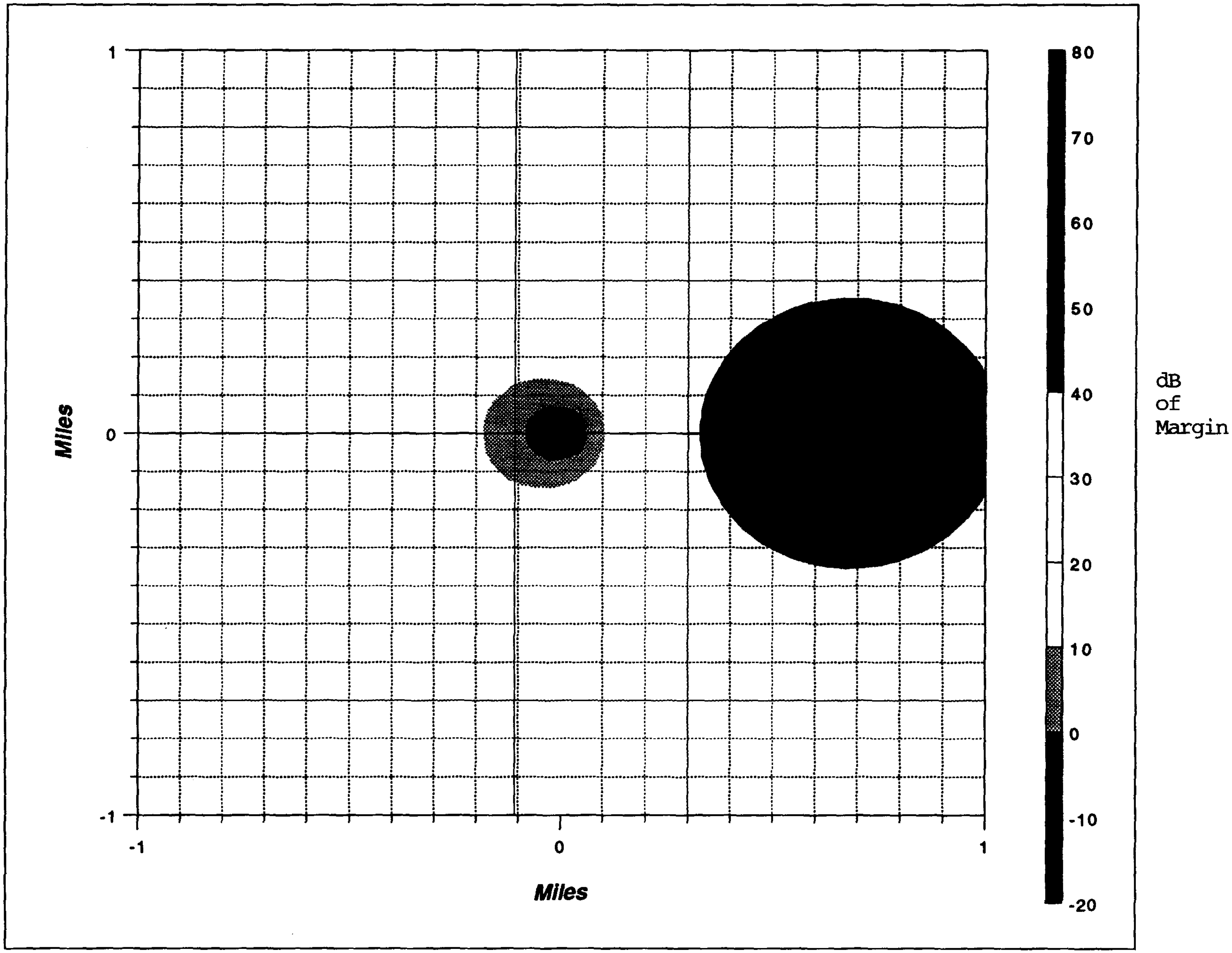
These contours are based on the following assumptions:

(1) The wide area base station's power level is fixed at 500w ERP with an omnidirectional antenna;

(2) The local-area reader's illumination is 1 w PEP with 32 w ERP, downward directed to the reader's target area about 30 ft in front of the reader mounted at a heigh of 10 ft. It is presumed that the signal's scattered off the vehicles in the target areas have significantly less directivity than, but similar power levels to, the illuminating beam; and

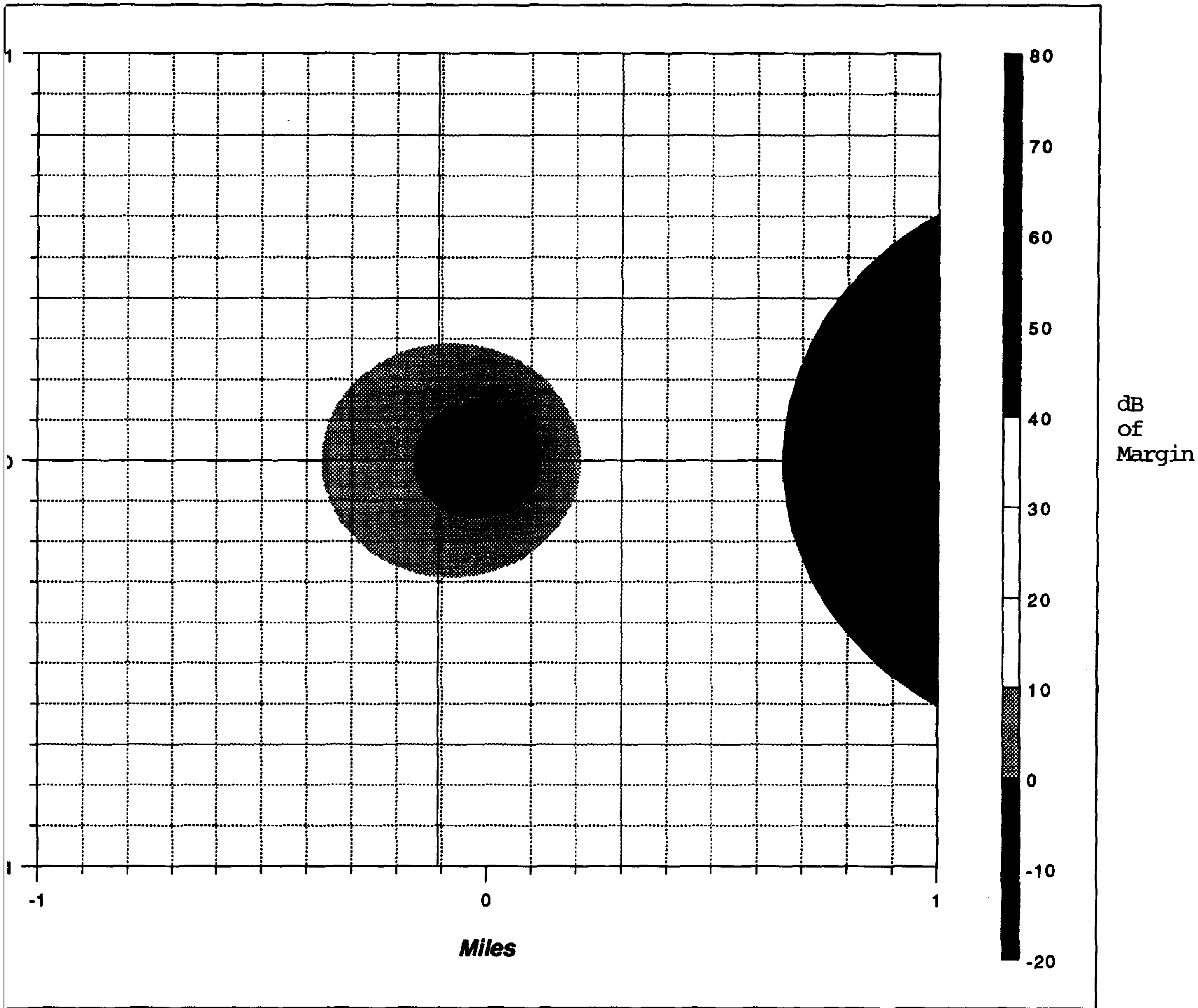
(3) Field measurements have shown that the signal path loss follows the typical 35 dB loss per distance decade for suburban areas, and average signal levels are those expected for a 30 dBm source.

It can be seen that the size of the black-out zone is very dependent on the spacing between the reader station and the wide-area base station. With the base station a half mile away (fig 1), the black-out zone is less than about 0.04 mile in radius (about 0.005 sq mile). At a mile spacing (fig 2) the area grows



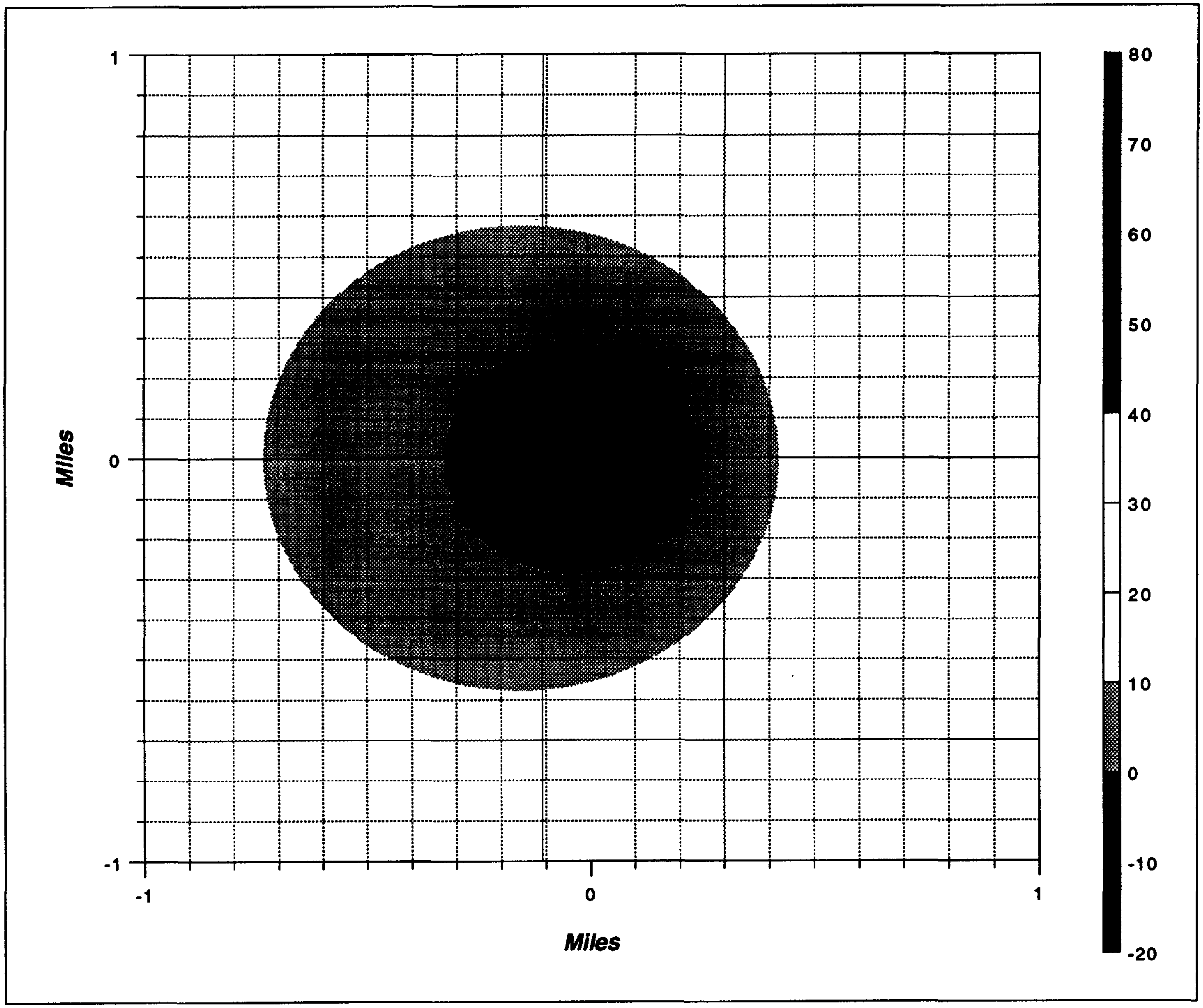
Miles from Reader Station

Figure 1



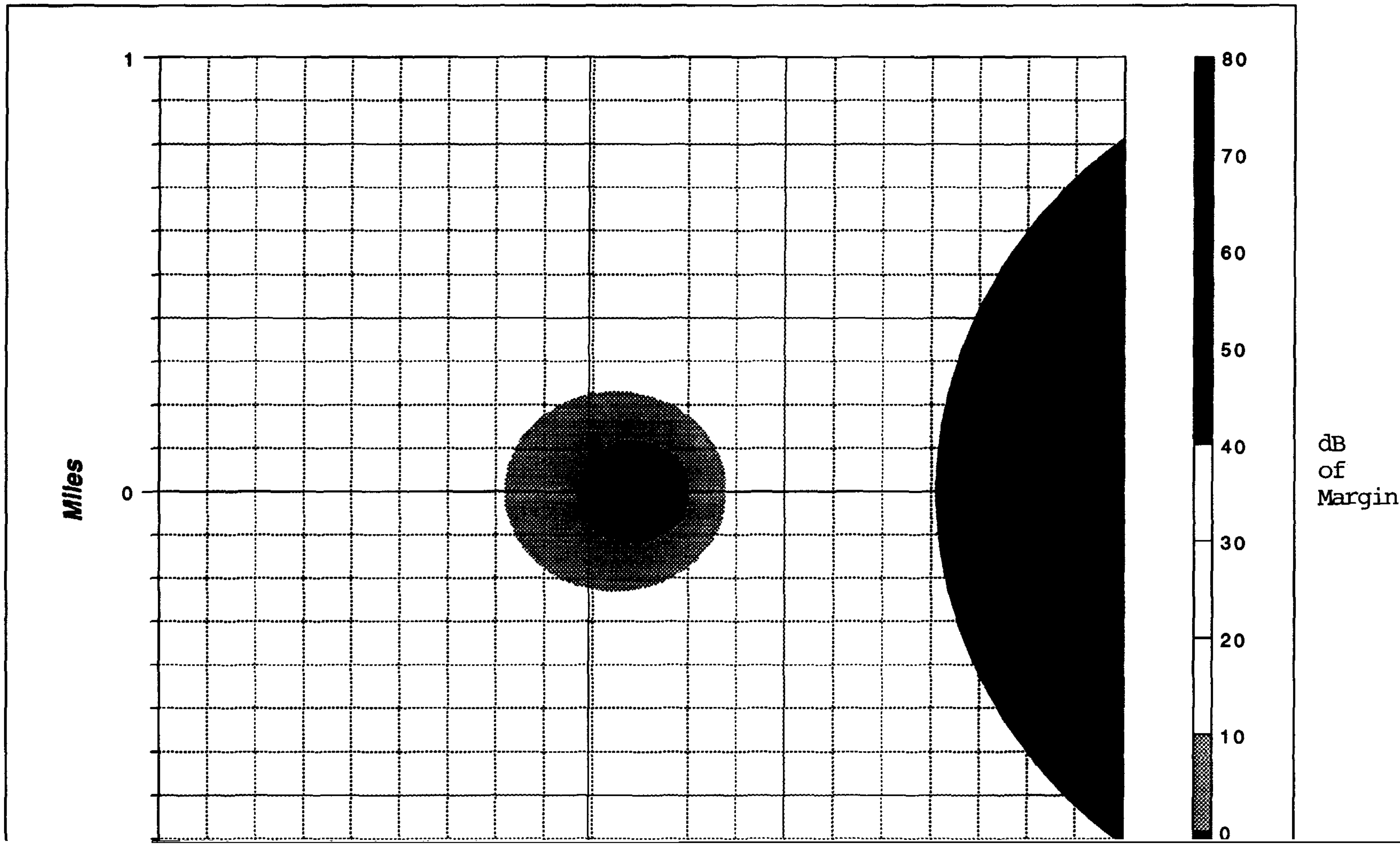
Miles from the Reader Station

Figure 2



Miles from Reader Station

Figure 3



Miles
1
0
80
70
60
50
40
30
20
10
0
dB
of
Margin

TAB

Exhibit D

Threshold Criteria for Wide Area Location and Monitoring Systems

Criterion for robustness: Demonstrated operation in a noise field of at least -85 dBm

Criterion for spectrum efficiency:

Number of successful reads/minute/MHz:

Bandwidth MHz	Location Fixes Per Second
2	20
4	70
6	140
8	230
10	340
12	470
14	620
16	790
18	980
20	1,190
22	1,420
24	1,670
26	1,940